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A REVIEW OF THE NATURE AND VARIABILITY OF THE ANELASTIC PROPERTIES OF THE UPPER MANTLE BENEATH NORTH AMERICA AND EURASIA

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20. ABSTRACT

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The available evidence for eastern North America indicates that a low velocity zone is either absent for that region or more poorly developed than it is in western North America. Most interpretations for P waves in eastern North America include no low velocity zone. Surface wave studies of the shear wave velocity structure beneath eastern North America indicate the possibility of a low velocity zone for S waves, at least in some regions.

The available data for northern Europe and Asia indicate that it is a stable region with velocity and attenuative properties much like those of eastern North America. The difference in attenuative properties of the upper mantle between the western United States and northern Asia might lead to higher m_b values for the Asian nuclear events than for equivalent NTS events, if the low velocity, low Q zone beneath the western United States is sufficiently thick and has low enough values. Thickness and Q values suggested by most published research can easily cause m_b values for events in the Basin and Range province to be a few tenths of a magnitude unit lower than events in shield regions.

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ABSTRACT

All reasonable mechanisms for producing low-velocity zones in the upper mantle should also produce zones of low Q. The available studies of upper mantle Q and velocity for the same regions suggest that a coincidence of low velocity and low Q zones does indeed occur.

Seismic body- and surface-wave data indicate a substantial low velocity, low Q zone in the upper mantle beneath western North America. The zone appears to be 150 km thick or more, the velocities for both P and S waves being lower than typical upper mantle velocities for stable regions.

The available evidence for eastern North America indicates that a low velocity zone is either absent for that region or more poorly developed than it is in western North America. Most interpretations for P waves in eastern North America include no low velocity zone. Surface wave studies of the shear wave velocity structure beneath eastern North America indicate the possibility of a low velocity zone for S waves, at least in some regions.

The available data for northern Europe and Asia indicate that it is a stable region with velocity and attenuative properties much like those of eastern North America. The difference in attenuative properties of the upper mantle between the western United States and northern Asia might lead to higher m_b values for the Asian nuclear events than for equivalent NTS events, if the low velocity, low Q zone beneath the western United States is sufficiently thick and has low enough values. Thickness and Q values suggested by most published research can easily cause m_b values for events in the Basin and Range province to be a few tenths of a magnitude unit lower than events in shield regions.

I. INTRODUCTION

The structure and properties of the upper mantle have been the subjects of much fruitful research in recent years. The mid- to late-1960's produced a marked increase in our knowledge of the velocity structure of the upper mantle. Research on the anelastic properties of that region has been less prolific, but much has been learned, especially since about 1970. The purpose of this report is to summarize some of those results, with emphasis on the nature and variability of the upper mantle low-velocity zone beneath North America. We will argue that this zone of low velocities coincides with a zone characterized by higher than normal attenuation, or low Q and is much better developed beneath western North America than beneath eastern North America.

Several references will be cited which present upper mantle models for eastern or western North America individually. Others will present comparative travel-time or attenuation data for the two regions. These studies will indicate distinct differences in the nature and vertical extent of the upper mantle low-velocity zone between eastern and western North America, whereas regional differences within either eastern or western North America will be much less pronounced. Only those studies will be considered which bear on the nature of the low velocity zone within either eastern or western North America. Long profiles which traverse both regions will not be considered.

Lateral variations in the nature and thickness of the upper mantle low-velocity zone will bear on an important practical aspect of seismology, namely that of magnitude determination. It is clear that those magnitude determinations are affected which are based on waves which traverse the low-velocity layer, namely m_b determinations. It will be seen in a later section that 20 second surface waves,

upon which surface wave magnitudes, M_s, are based, exhibit no great variation from one continental region to another.

Research on other geophysical parameters also indicates distinct differences in the upper mantle between eastern and western North America. These will be discussed and their relationship to certain crustal properties will also be presented.

The stable regions of eastern North America will be compared to other stable regions of the world. The available evidence will suggest that crustal and upper mantle velocity and Q structures beneath the stable regions of the world do not greatly differ from one another.

II. RELATIONSHIP BETWEEN ZONES OF LOW VELOCITY AND LOW Q IN THE MANTLE

The Q structure of the upper mantle can be inferred from body wave or surface wave amplitudes. Although the study of these dynamic properties of seismic waves supports the conclusions of this report, the number of such studies is far smaller than the number of studies of kinematic properties, namely body wave travel-time and surface wave dispersion, which depend on elastic properties of the upper mantle. It will be useful then, to establish the coincidence of zones of low velocities and low Q values in the upper mantle. This will greatly increase the number of studies to which we can appeal. In addition, since travel-time and dispersion data are subject to far fewer uncertainties than amplitude data, the results of various studies can be viewed with greater confidence.

Intuitively, we might suspect that low Q zones and low velocity zones in the upper mantle might coincide because it seems likely that material with low rigidity and low bulk modulus values would also be characterized by low Q values. However, I will attempt to show the coincidence of low velocity and low Q zones in two ways. First, I will present results from two regions in which both velocities and Q values have been obtained for the upper mantle low velocity (and low Q) zone. Secondly, it will be seen that the most widely accepted mechanism for the low velocity zone in the upper mantle will also produce low Q values.

Comparisons between velocity and Q structure of the upper mantle are limited by the small number of Q models for specific regions. The Pacific and the western United States appear to be the only regions where Q models and velocity models for the upper mantle can be compared.

The average Pacific model of Mitchell [1976] includes a low Q zone at depths between 60 and 220 km. This can be compared with the Pacific velocity models of Saito and Takeuchi [1966], which include low velocity zones over a similar depth range.

Archambeau, et al. [1969] found a low Q layer in the western United States which roughly coincides with a P wave low velocity layer. Lee and Solomon [1975] inverted attenuation data in the western United States to obtain a model having a low-Q zone at depths between 85 and 160 km. Upper mantle velocity models for that region, such as those derived by Masse, et al. [1972] and Helmberger [1973] include low velocity zones over a similar depth range.

Anderson [1967] has suggested that a low Q zone can be expected for almost any mechanism used to explain low velocities, including high temperatures or high thermal gradients. Later work [Anderson and Sammis, 1970] has shown that velocities in the low velocity zone are too low to be explained by any reasonable minerology or temperature gradient, and conclude that this zone is best explained by partial melting or by the presence of water produced by dehydration processes. Either mechanism can also be expected to produce a reduction in Q values.

III. EASTERN NORTH AMERICAN UPPER MANTLE MODELS

Most of eastern North America is considered to be a relatively stable region and includes the Canadian shield. As shown in a later section, available evidence suggests that other stable regions such as the Eurasian and African sheilds are characterized by similar velocity and Q structure in the upper mantle.

Compressional (P) wave velocity models of the upper mantle have been determined largely from long seismic refraction lines using explosive sources. Most of these, such as the interpretation of Green and Hales [1968], Barr [1967], Mereu and Hunter [1969] and Roller and Jackson [1966], require no low-velocity zone for P waves in this region. The model of Masse [1973] includes a low velocity zone, but it is thin and poorly developed. These models are summarized in Figure 1, taken from Masse [1973].

Shear (S) wave velocity models are most often inferred from the dispersion of surface waves. Modest zones of low shear velocities for the upper mantle beneath the Canadian shield and central United States are included in models derived by Brune and Dorman [1963] and McEvilly [1964], respectively. Biswas and Knopoff [1974] found, however, that a low-velocity zone is not required beneath the central United States, although one is required beneath the Gulf Coast region.

The only Q model which pertains to the upper mantle beneath eastern North America was derived by Lee and Solomon [1975] using previously published attenuation data. Although much scatter is present, an adequate fit to the data does not require a low-Q zone in the upper mantle. Two eastern United States models appear in Figure 2, which is reproduced from Lee and Solomon [1975].

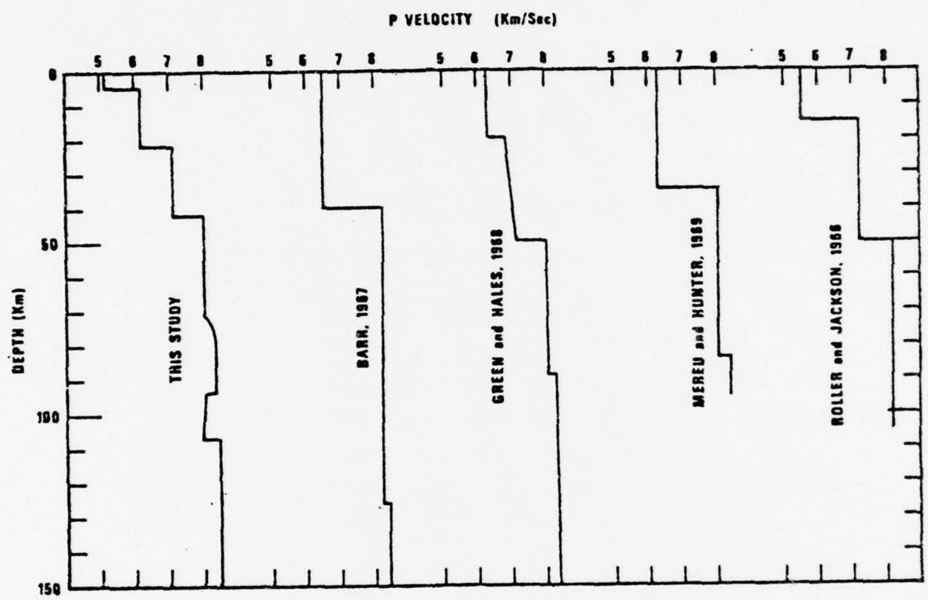

Figure 1. P wave velocity models for eastern North America (from Massé [1973], reproduced with permission from Bull. Seism. Soc. Am.).

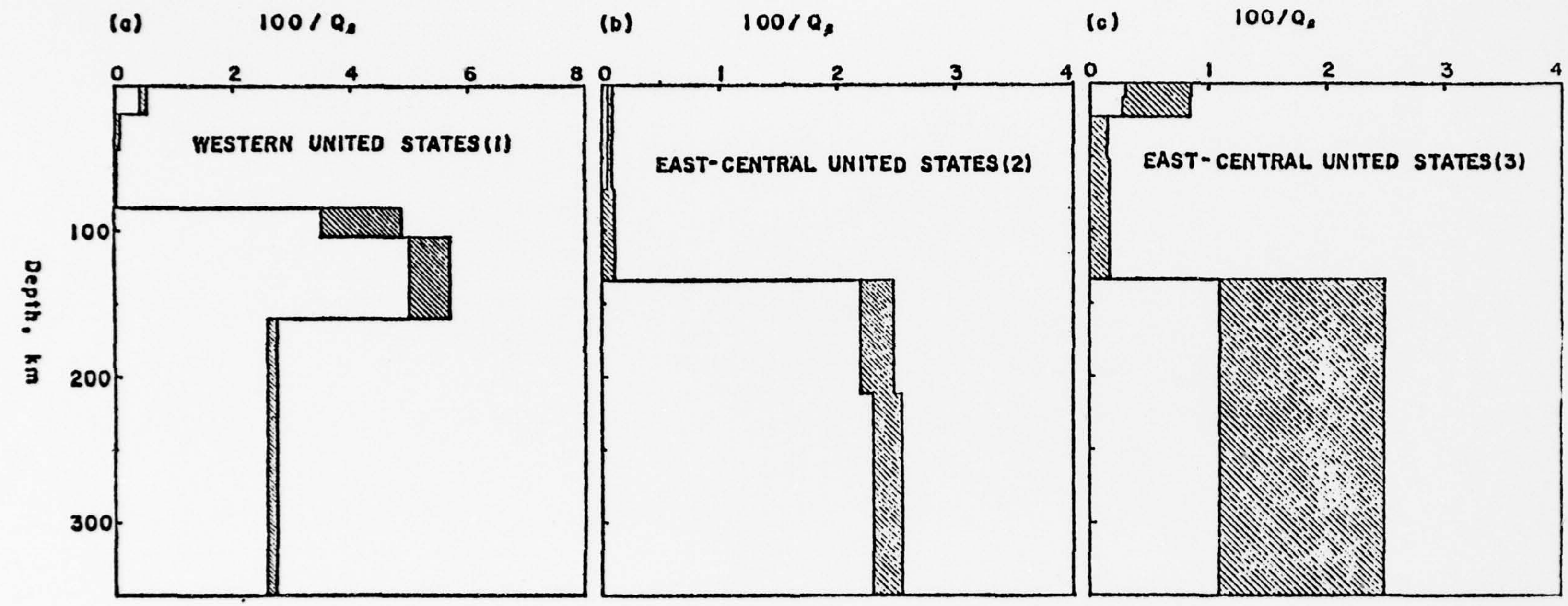

Figure 2. Attenuation models for the eastern and western United States. The shaded regions indicate the envelope of models which are consistent with each data set (after Lee and Solomon [1975], reproduced with permission from <u>Geophys. J. Roy. astr. Soc.</u>).

The presently available seismic data for eastern North America favor an upper mantle with a modest shear wave low velocity zone, at least in some regions. Most interpretations using P wave data, however, suggest that a P-wave low-velocity zone is not present, although a poorly developed low-velocity zone can probably not be ruled out.

IV. WESTERN NORTH AMERICAN UPPER MANTLE MODELS

In contrast to eastern North America, virtually all P-wave upper mantle models derived for western North America, or portions of that region, include well-developed low-velocity zones. These include models derived by Archambeau, et al. [1969], Masse, et al. [1972] and Helmberger [1973]. Substantial differences occur between various upper mantle models for the western United States, particularly with regard to the thickness of the low-velocity zone and the thickness of the lid above it. In all cases, however, a low-velocity zone for P waves is present and well-developed. These are summarized in Figure 3.

A shear wave velocity model of the mantle beneath the western United States has been obtained by Biswas and Knopoff [1974] by inverting long-period surface wave phase velocity data. Although the details of their model are uncertain, it is clear that a prominent low-velocity zone for shear waves is required. This result is in contrast to their model of the mantle beneath the north-central United States, for which a low-velocity zone is either absent or poorly developed.

Further information on the shear wave structure beneath the western United States was obtained by Yasar and Nuttli [1974] who studied shear-wave travel-time residuals. They found significant variations in the thickness of the shear-wave low-velocity channel, the greatest thickness occurring in southern Utah and Nevada and in northwest Arizona.

The Q model of Lee and Solomon [1975] for the western United States appears in Figure 2 along with the eastern United States models. In contrast to the model for the eastern United States, a substantial zone for low Q values appears to be required beneath the western United States.

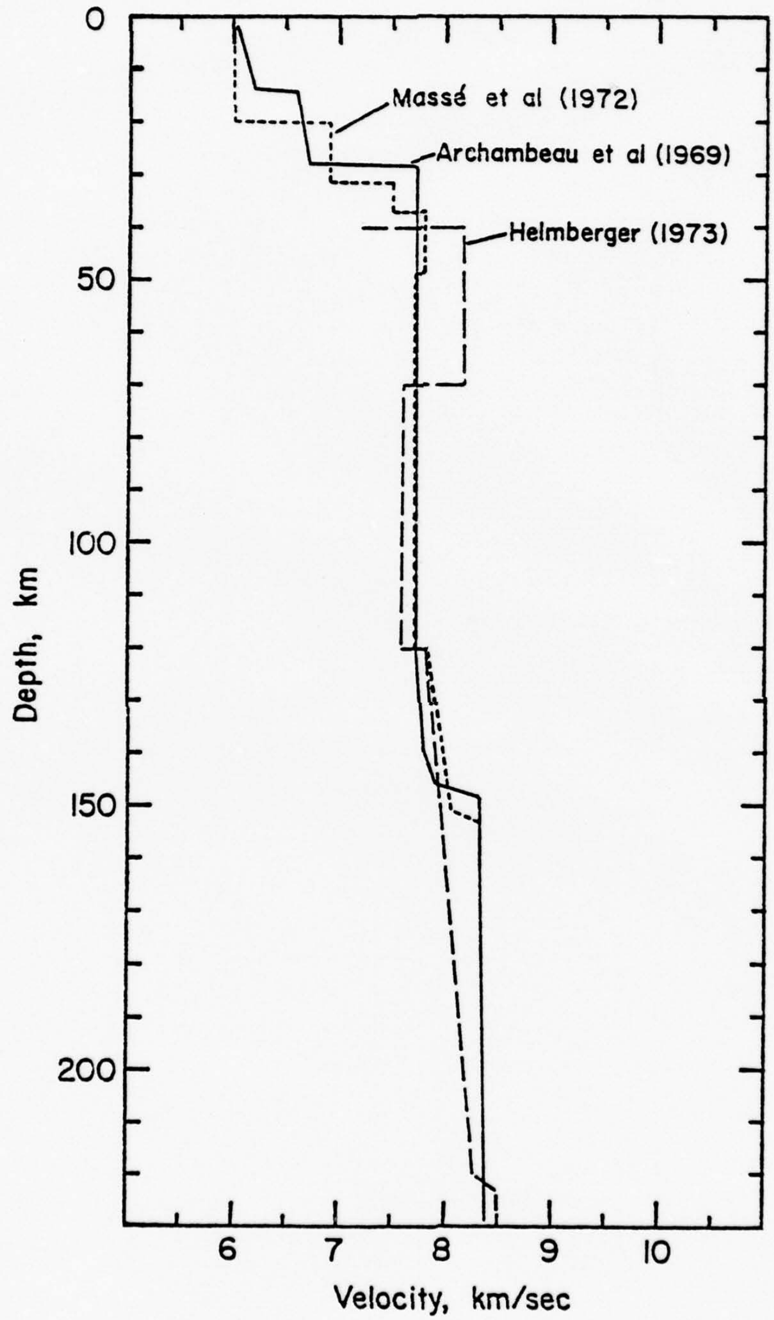

Figure 3. P wave velocity models for western North America.

Additional seismic data pertaining to the upper mantle beneath the western United States have been obtained by York and Helmberger [1973]. They observed time differences between P and PL waves on several seismograms recorded in the southwestern United States. They compared the nearly constant velocity of the PL wave in the crustal wave guide with the regionally variable long-period P wave velocity, to obtain a contour map of large-scale variations in the upper mantle. They concluded that the thickness of the upper-mantle low-velocity zone is variable beneath the southwestern United States, being thickest beneath the Basin and Range province and thinner in other regions. The region beneath which the low-velocity zone is best developed includes the Nevada Test Site.

V. COMPARATIVE STUDIES OF THE UPPER MANTLE BETWEEN EASTERN AND WESTERN NORTH AMERICA

Several comparative studies of teleseismic P and S waves have also been made for North America. It will be seen that these substantiate the lateral differences in velocity and Q structure of the upper mantle beneath North America as inferred from the individual studies of eastern and western North America discussed in the previous sections.

Cleary and Hales [1966] observed regional variations in P wave travel-time residuals across North America. The arrivals were as much as a second early in the central United States and up to a second late in the Basin and Range province. Doyle and Hales [1967], in a similar study of S waves found a range of travel-time anomalies of about 8 seconds, with negative values generally occurring in the eastern and central United States and positive values occurring in the western United States. These are most easily explained by lateral variations in the velocity structure of the upper mantle. Birch [1969] suggested that partial melting in the upper mantle beneath the western United States is a likely explanation for the travel-time anomaly data.

The relative attenuation of body waves passing through the upper mantle beneath North America has been the subject of at least three studies. Solomon and Toksöz [1970] determined a differential attenuation

$$\delta t^* = \pi \int_{\text{path}} \delta Q_\beta^{-1} (s,f)\ \beta^{-1} (s)\ ds$$

where β is the shear velocity and δQ_β^{-1} is the departure of the true anelasticity, at a point along the ray path, from a radially symmetric Q_β^{-1} distribution. Positive values

indicate greater than normal attenuation and vice versa. Their results, for both P and S waves, indicate high attenuation between the Rocky Mountains and the Sierra Nevada-Cascade ranges and low attenuation throughout most of the central and eastern portions of the United States.

Der, Massé, and Gurski [1975] observed consistent patterns of attenuation for short-period teleseismic P and S waves. Their analysis showed that greater attenuation occurs for both types of waves in the western United States than in the eastern United States. In a later study, Der and McElfresh [1976] determined average Q values for ray paths from the SALMON nuclear explosion to various LRSM stations. They obtained average Q values between 1600 and 2000 for paths confined to eastern North America, whereas they obtained values of 400 to 500 for paths crossing over into the western United States. Figure 4, reproduced from Der, et al. [1976] dramatically illustrates the attenuation of high frequency waves for paths traversing the upper mantle of the western United States (NW profile) as compared to the same frequencies for the other paths.

It is a straightforward procedure to calculate the reduction in m_b values produced by passage of a compressional wave through a zone of low Q. If we assume that a layer has constant values for both velocity and Q, then the compressional wave amplitude, for a wave traversing that layer, is reduced by the factor

$$F = e^{-\frac{\pi f x}{Q\alpha}}$$

where f is frequency, α is compressional wave velocity, and x is the distance traveled through the layer. If we take x to be 150 km, f to be 1 Hz, and α to be 7.6 km/sec, then the amplitude reduction factor above can be calculated for

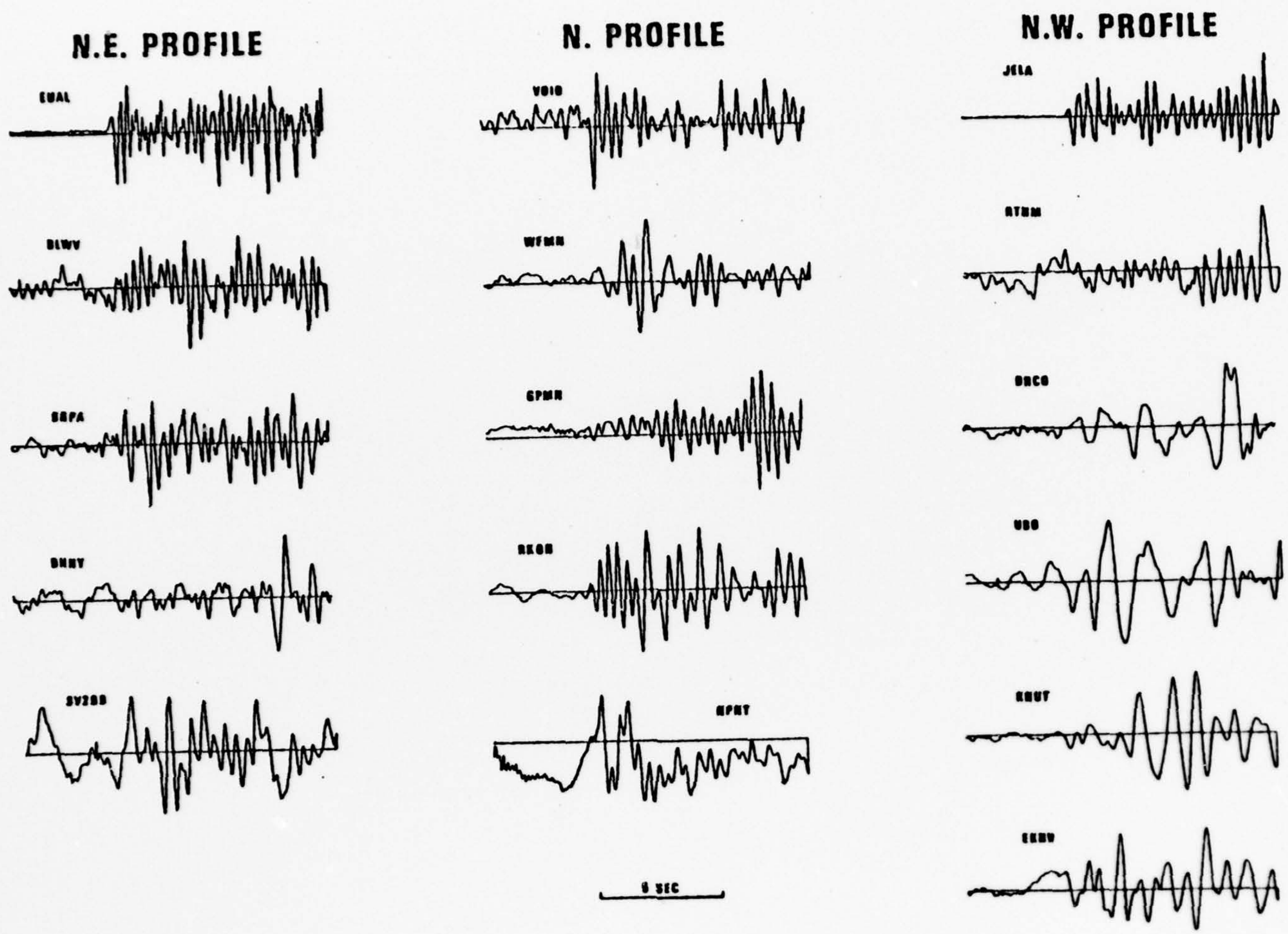

Figure 4. Seismograms along three profiles from the SALMON nuclear explosion (after Der and McElfresh [1976], reproduced with permission from Bull. Seism. Soc. Am.).

any given value of Q. Table 1 presents the results of a few sample calculations. These results indicate that a 150 km thick layer having a Q value of about 500 or more will cause only a very small reduction in amplitude. A Q value of 20, on the other hand, would have a drastic effect on compressional wave amplitudes.

Body wave magnitudes have been defined by Gutenberg [1958] to be

$$m_b = \log_{10}(A/T) + \bar{Q}\ (\Delta,h)$$

where A/T is the amplitude-to-period ratio and $\bar{Q}$ is a calibration function which is a function of epicentral distance (Δ) and depth (h). $\bar{Q}$ can be obtained from available tables.

If observed compressional wave amplitudes, A_1 and A_2, lead to magnitude determinations $(m_b)_1$ and $(m_b)_2$, the difference is these determinations can be expressed as

$$\Delta m_b = (m_b)_2 - (m_b)_1 = \log_{10} \frac{A_2}{A_1} .$$

If the amplitude differences are produced by different Q values in a 150 km thick layer, then

$$\Delta m_b = \log_{10} \frac{F_2}{F_1}$$

where F_1 and F_2 are the amplitude reduction factors described above. If F_1 corresponds to a shield region and F_2 corresponds to the Basin and Range province, we can calculate expected differences in m_b obtained for paths through the two regions. Table 2 lists some results for various combinations of Q values which might represent a shield region and the Basin and Range province.

TABLE 1

Amplitude reduction factor produced when a compressional wave travels 150 km through a region of constant velocity and Q. The velocity is taken to be 7.6 km/sec.

Q	Amplitude Factor, F
20	0.05
50	0.29
100	0.54
300	0.81
500	0.88
1000	0.94

TABLE 2

Differences in m_b which would be expected between two regions for which the Q values are different for a 150 km segment of the path of compressional waves. Q_1 values might be taken as representative for the upper mantle beneath eastern North America and Q_2 might represent those beneath western North America

Q_1	Q_2	F_2/F_1	Δm_b
1000	50	0.31	-0.51
1000	100	0.57	-0.24
500	50	0.33	-0.48
500	100	0.61	-0.21
300	50	0.36	-0.45
300	100	0.67	-0.18
100	20	0.09	-1.03
100	50	0.54	-0.27

The calculations of Table 2 indicate that it is not difficult to obtain differences in m_b of 0.2 units or more by using realistic values of Q for shield regions and the Basin and Range province. In fact, many of the δt^* values observed by Solomon and Toksöz [1970] would lead to a much greater difference in m_b.

VI. OTHER GEOPHYSICAL STUDIES

Two other properties which might vary laterally throughout the upper mantle are electrical conductivity and temperature. Porath and Gough [1971] and Gough [1973] have proposed higher conductivities for the western United States relative to the eastern United States, based upon geomagnetic deep sounding measurements. Their simplified models indicate that resistivity values of 5 ohm-meter occur at much shallower depths beneath the Basin and Range than beneath the Great Plains. They suggest that the depths obtained are consistent with laboratory studies of the variation of sensitivity of olivine with temperature, lower sensitivity values being produced by higher temperatures at a given depth.

Heat flow measurements [Blackwell, 1971] are consistent with the resistivity model. They appear to be higher for most of the western United States than they are for the stable regions of eastern North America. Zones for low Q should also be more likely to occur in regions where heat flow is high, either as a result of high temperatures, or because of partial melting or the presence of water produced by dehydration at high temperatures.

VII. CRUSTAL ANELASTICITY

Mitchell [1975] showed that Rayleigh wave amplitudes at periods less than 15 seconds are attenuated more rapidly in western North America than they are in eastern North America. At periods of 5 seconds, amplitudes in western North America are only one fifth as large as those in eastern North America for a 1000 km path. Those observations reflect variations in Q values in the upper crust. Longer periods, up to at least 30 seconds, on the other hand, exhibit little regional variation, since they are strongly influenced by higher Q values of the lower crust [Solomon, 1972; Mitchell, 1975]. Since 20 second surface waves do not appear to be greatly affected by regional variations in anelasticity, we can also expect that M_s values determined for that period will exhibit no great regional variations.

VIII. COMPARISON WITH EURASIA

Much fewer data are available from which to infer the crustal and upper mantle structure beneath Eurasia than are available for North America. However, the data which are available suggest that much of northern Europe and Asia (including the Russian nuclear test sites in central Asia) is similar in its properties to other stable regions of the world, such as eastern North America.

Gupta and Sato [1968] used Love wave group velocities at periods up to 60 seconds to regionalize Eurasia according to its dispersion characteristics. They found that the Himalayas and Tibetan Plateau regions are characterized by extremely low group velocities, whereas much of northern Europe and Asia is characterized by velocities which are typical of stable regions. This work supported a previous regionalization of Eurasia based upon Rayleigh waves [Santo and Sato, 1966].

A recent study by Gupta, *et al.* [1977] used surface waves with periods as great as 300 seconds. They found that a shield-like upper mantle structure was required for a large region of southern Asia which includes the south Indian shield and the Indogangetic plains.

The only study of surface wave attenuation confined to Eurasia appears to be that of Yacoub and Mitchell [1977]. While there is considerable scatter in the data, the results indicate that the anelastic properties of the crust in the stable portions of Eurasia are not greatly dissimilar from those in eastern North America, whereas the tectonically active regions may be characterized by somewhat greater attenuative properties.

Heat flow determinations for Eurasia are rather sparse. However, the values reported for Eurasian shield regions by Lubimova and Polyak [1969] are consistent with those for other shield regions.

The little geophysical data that are available for Eurasia, then, suggest that the northern stable regions are much like eastern Northern America in their properties. In particular, we might expect the Q structure of the upper mantle beneath much of northern Europe and Asia (including the Russian nuclear test sites in central Asia) to be characterized by higher Q values than those which occur beneath the Nevada Test Site.

IX. CONCLUSIONS

The available seismic and other geophysical data overwhelmingly suggest that the properties of the upper mantle beneath the western United States (and especially beneath the Basin and Range province) are quite different than those beneath more stable regions. Those differences include lower velocities and lower Q values for western North America than those expected for eastern North America or the stable regions of Eurasia.

Differences in Q for the upper mantle in these regions which might be expected from available evidence, are great enough to produce differences in m_b values between events which occur in stable regions and those which occur in the Basin and Range province. The lower Q values for the upper mantle beneath the Basin and Range province could easily lead to m_b values for NTS events which are a few tenths of a magnitude unit lower than events of the same yield which occur in shield regions.

Surface wave amplitudes at periods of 20 seconds are governed largely by the shear wave internal friction (Q_β^{-1}) values in the lower crust. Those values are much lower and more uniform than the Q_β^{-1} values in the upper crust; consequently the amplitudes of 20 second surface waves and the M_s determinations from them exhibit little variation from one continental region to another.

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